Chapter 2
Pipe Inspection Robots for Gas and Oil Pipelines

2.1 Introduction

Energy-related utilities such as fuel, gas, or oil supply lines and power generation sources such as nuclear and thermal power plants require an extensive network of pipelines for various transportation purposes. Figure 2.1a shows a typical network of pipelines generally used for oil and gas transportation.

These networks are in fact quite vast for any industrially developed country. The vastness of such operation in a developed country like USA is brought out in Fig. 2.1b.

Transportation of natural gas by pipelines is rapidly increasing in developing countries like India. Figure 2.1c shows the extent of Gas pipelines in India extracted from the International Energy Agency Report of 2010. Currently, India has about 11,000 km of gas pipelines. These pipelines, however, have limited life due to various types of static and dynamic loads originated from both inside and outside the pipe, as well as due to natural processes of degradation such as oxidation and corrosion of the pipe surface, and joint failures due to abrasion. The presence of internal defects/corrosion in a gas pipeline is generally detected by:

- Visual examination using inspection dig,
- External measurement such as electrical survey,
- Examination of corrosion coupons or probes placed inside the pipeline,
- Use of in-line inspection tool to identify areas of pitting or metal loss.

In this book, we will deal with various technologies developed specifically for in-line inspection.

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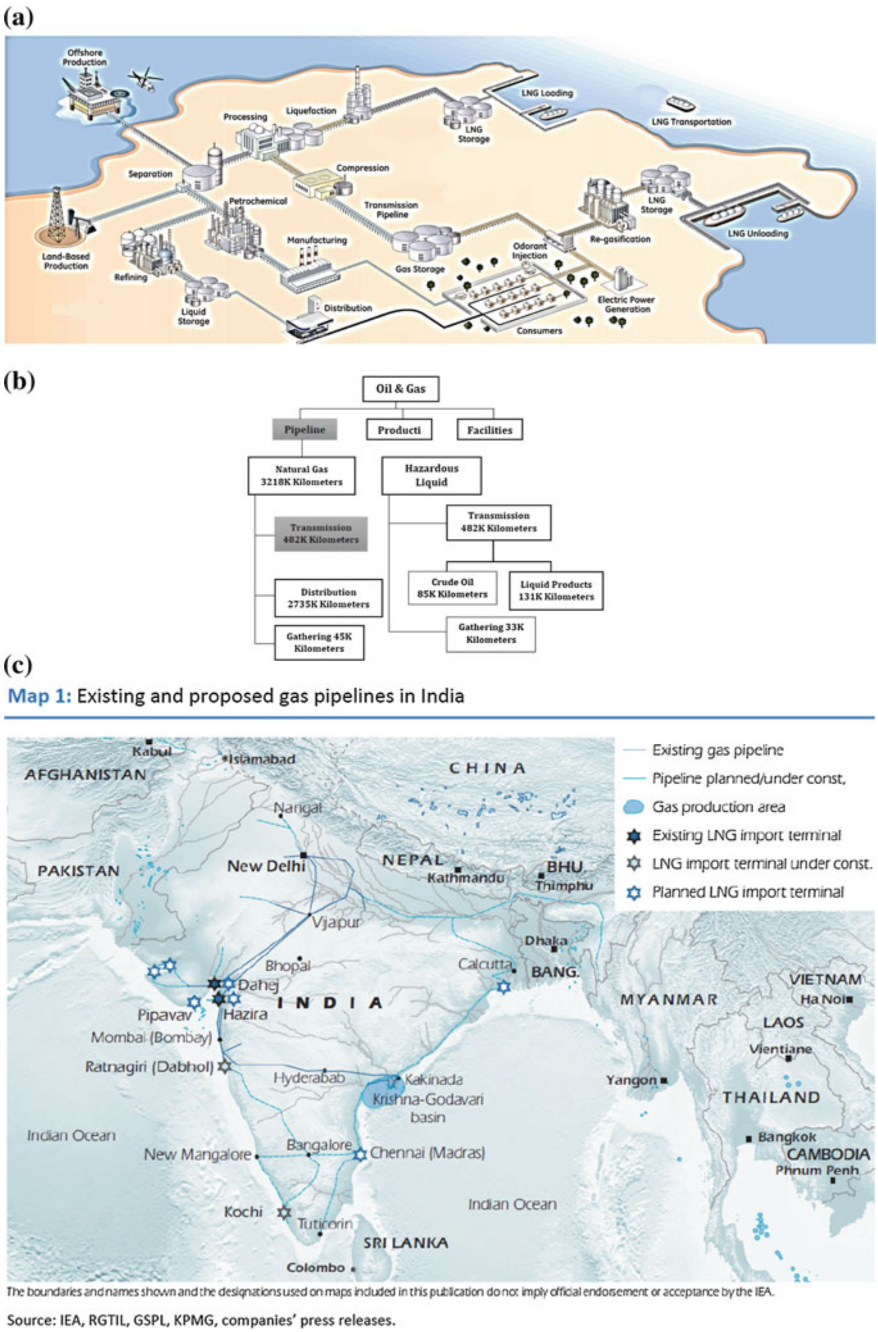


Fig. 2.1 **a** A typical pipeline network for oil and natural gas. **b** Oil and gas pipelines in USA (1998) [1]. **c** The extent of gas pipelines in India

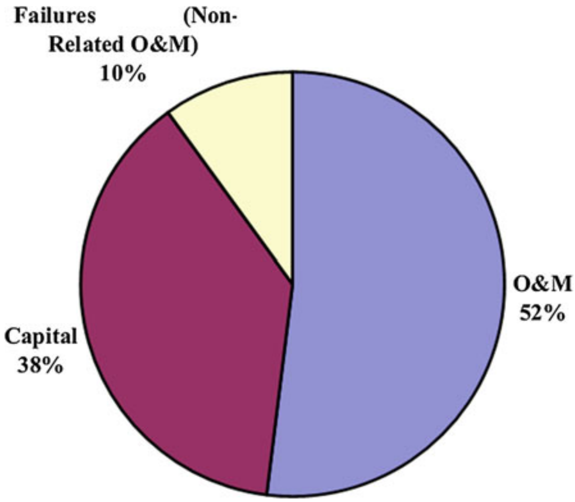


Fig. 2.2 Pattern of corrosion-related expenses in oil and gas pipelines [1]

The concept of structural health monitoring (SHM)[1] is immensely applicable in these fields to improve the life span of the pipelines and prevent catastrophic failures. As it is nearly impossible to equip the entire pipeline with distributed array of sensors, a better strategy that has been envisaged is to monitor the condition of the inner surface of the pipe with the help of a surveillance robot. A couple of decades ago, this technique was first introduced in nuclear power plants with the help of cable-drawn wheeled carts having a camera recorder at their apex. However, with the advent of sensors and actuators, fully autonomous robots based on various motion generation systems and integrated with multiple sensors are being developed today. Some of these robots travel hundreds of kilometers inside the pipelines to record the surface condition and location of damages. It may be understood from Fig. 2.2 that the operation and management of the oil and gas pipelines take up the major part of the expenses (more than 50%) in the transmission of oil and gas transport. Hence, a considerable research funding is allocated worldwide to find newer and cheaper ways of monitoring the pipelines to ensure safety and high performance of the system.

Such in-line monitoring system generally consists of two major subsystems—traction generation/locomotion system and damage sensing system.

The traction generation/locomotion system may be further classified into two broad categories: conventional locomotion and non-conventional locomotion. Conventional locomotion is further subdivided to three types:

(a) Wheel drive locomotion,
(b) tractor/truck-driven locomotion, and

[1]SHM is a complete process of design, development, and implementation of techniques for the detection, localization, and estimation of damages which is used in monitoring the integrity of structures and machines.

(c) Fluid-powered propulsion.

Non-conventional locomotion systems are more advantageous for very narrow (less than 100 mm diameter) and complex network of pipelines. Three such reported systems are as follows:

(a) Clamp and pull system similar to inchworm motion (speed 80 mm/s),
(b) Multi-legged system,
(c) Smart-ball system.

In the following sections, we will discuss various locomotion systems at length.

2.2 Traditional Locomotion Systems

Wheel drive locomotion system is one of the most commonly used techniques for driving pipe-crawlers. Figure 2.3a shows a typical wheel drive traction robot. These robots are generally used for large diameter pipes such as drainage pipes. They are also good for variable pipe diameters and high-speed driving. Maximum speed of such robots recorded in open literature is around 163 mm/s (approximately about 0.6 km/h!). In fact, for medium-sized pipes, the speed is even low about 30–80 mm/s. Of course, for effective SHM, forward speed is not of much concern as higher speed may compromise the accuracy of damage detection. A subgroup of wheeled robots is of the pressed-fit type (Fig. 2.3b) and is especially suitable for curved pipes and vertical climbing.

For uneven and greasy or muddy pipe surfaces, often better grips are required. In such cases, tractor/truck-driven systems are more useful. Figure 2.4 shows a typical belt-driven system. Such robots are also resource-effective from the manufacturing point of view as they are not only simple in design but also have a better load-carrying capacity than wheel drive systems. However, these robots are generally slower than the wheel-driven robots (recorded max speed is around 40 mm/s).

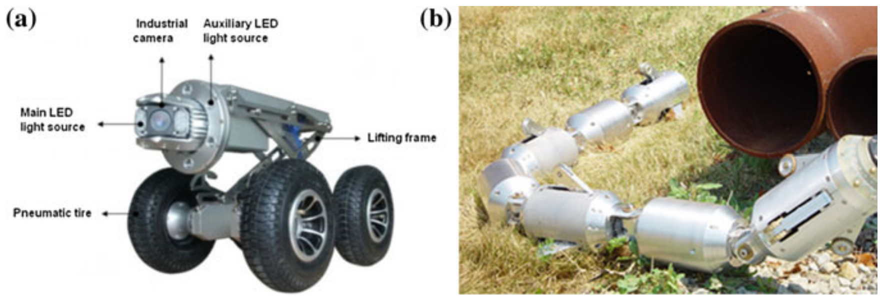


Fig. 2.3 **a** A typical wheel-type pipe inspection robot with an onboard camera system, **b** a pressed-fit wheeled robot system [2]

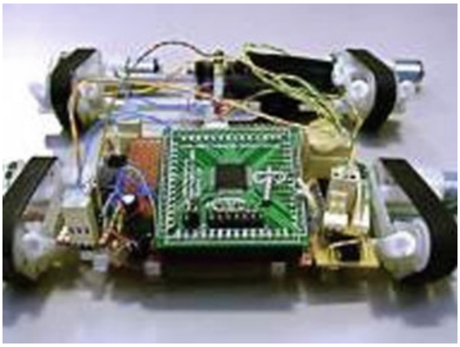


Fig. 2.4 Belt-based crawler robot [3]

Propulsion-driven systems are generally used in relatively large diameter water and gas pipelines. For such applications, passive robots are developed that can mostly extract the flow energy for locomotion. Pipe Investigation Gauge (PIG) as shown in Fig. 2.5 is one such example. The weight of each module of the robot is limited by the kinetic energy available from the flow.

2.3 Non-conventional Locomotion

Clamp and pull systems are generally used in smaller pipelines where the space is limited and the flow energy is not sufficient to pull the robot. This system is essentially very similar to the inchworm movement which generates motion by a sequence of rear clamping–expanding and front clamping–pulling action. Figure 2.6a shows a typical miniaturized clamp and pull robot. There are numerous systems designed to accomplish this motion. However, the basic concept remains the same. Figure 2.6b shows the five-stage sequence of inchworm motion in a SMA-activated modular system.

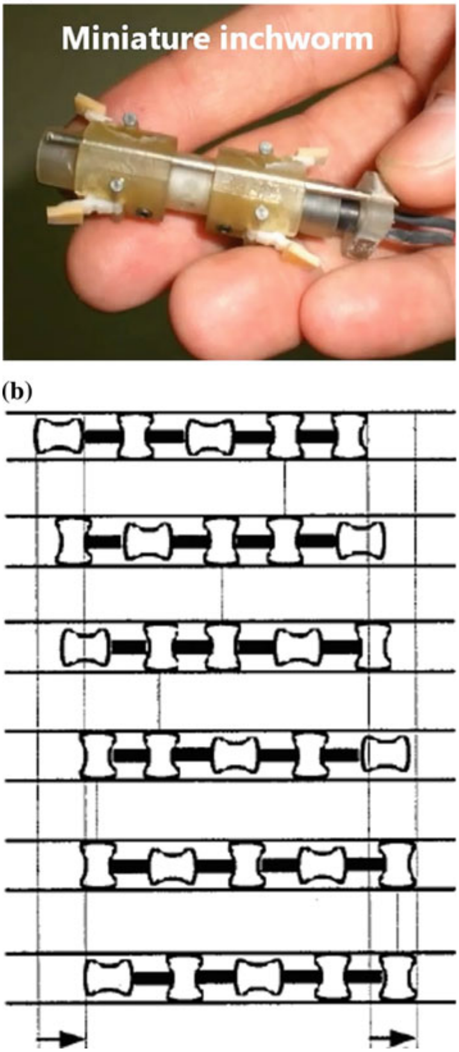
There are a few other exotic varieties of the motion generation system such as walking robots equipped with legged motion. These types of robots are specially

Fig. 2.5 A propulsion-driven PIG system with magnetic flux sensors

Fig. 2.6 **a** A miniature inchworm robot developed at Technion [4]. **b** A five-stage inchworm motion based on SMA

(a)

(b)



suited for uneven surfaces and pipes with complex connections. A few of these legged variations of walking robots are shown in Fig. 2.7a–c.

The legs are used to press against the pipe wall to provide enough traction for the robot to climb or walk inside a pipe or duct. Unlike most of the visual feedback-based robots, movement of this robot is based on tactile sensing at the feet and contact sensing along the legs. The control of the robot is generally divided into three control units: the main control unit, the leg control unit, and the force/velocity control unit. During motion, at a very local level, each individual leg lifts itself and tries to judge the stability of the robot. If the stability is compromised during several

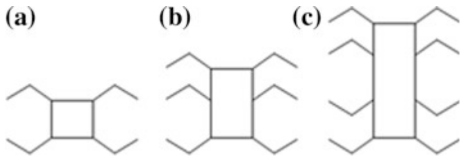


Fig. 2.7 **a–c** 4, 6, and 8 legged robots

trials, then the main control unit is informed about the change of stance. It is found that articulated leg-type robot with such reflexive behavior can easily pass through obstacles such as bends, diameter variations. However, generation of power and manufacturing complexity of the leg system are two of the major hindrances to the development of this technology.

Smart-ball leak detection [5] is a free-flowing system used to locate leaks and gas pockets in pressurized pipelines (see Fig. 2.8). It can complete long leak detection surveys in a single deployment without disrupting regular pipeline service. The tool is equipped with highly sensitive acoustic sensor that is able to locate 'pinhole'-sized leaks. The Smart-ball is inserted into a pipeline and travels with the water flow for up to 12 h while collecting information about leaks and gas pockets. It requires only two access points, one for insertion and the other for extraction, and is tracked throughout the inspection at predetermined fixed locations on the pipeline.

The detection system consists of an inner aluminum alloy core containing an acoustic sensor and circuitry. The aluminum core is in turn encapsulated inside a foam ball. The foam ball provides the appropriate mass (size and overall weight) that allows the device to be propelled by the water flow. It also absorbs any noise that the device may make as it traverses through the pipeline. While the ball is traversing inside the pipeline, a transponder within the Smart-ball core emits high-frequency, timed acoustic signals that are detected by Smart-ball Receivers (SBRs) on the pipe surface. The Smart-ball Receivers track the Smart-ball's movement and location, correlating its position at any time with reference to acoustic events recorded on the acoustic sensor contained within the Smart-ball. Once the Smart-ball has traversed the entire length of the pipeline, it is typically captured and retrieved either in a specially engineered net or in an open channel. The recorded data are subsequently evaluated to determine the presence and location of leaks or pockets of trapped gas. Smart-ball requires a minimum of 100 mm flange opening with a full port valve for insertion into the pipeline. Once deployed, it can move through in-line valves, reducers, and other fittings, as well as navigate through turns and profile changes.

In the following section, we will have an elaborate discussion of a few more complex traction mechanisms.

2.4 More Complex Traction Systems

In this section, we will discuss some complex locomotion systems which are primarily based on the conventional locomotion systems described earlier. These are, however, more complex in nature since in addition to simple translation motion, they have to perform additional functions. Out of numerous multi-function locomotion systems, the following four are found to have many industrial applications:

(i) Adaptive system—to move inside variable diameter pipes,
(ii) Active steering system—that can take care of bends and branches,
(iii) Self-retrieval and obstruction mitigation system and finally,
(iv) Vertical climbing system.

In what follows is a brief description of some of the multi-functional robots developed at various robotics laboratories.

2.4.1 Three-Wheeled Self-adjusting Vehicle for Variable Pipe Diameter

A three-wheeled robot (FERRET-1), [6] whose shape looks like the alphabet '**A**' is shown in Fig. 2.9. At the end of the two legs, spherical bearings are installed, and depending on whether the vehicle type is tractive or non-tractive, a driving wheel or another spherical bearing is installed at the vertex joining the two legs. The two legs are connected by a spring between them. The purpose of the spring is to provide enough tractive force on the wheels so that the wheels do not slip. Two different types of driving wheels are considered in this design which can guide the vehicle posture to the maximum diameter of the pipe.

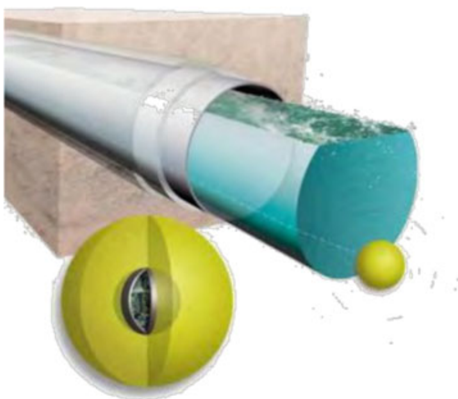


Fig. 2.8 Smart-ball Technology [5]

2.4.2 MOGRER—A More Complex Variant of the FERRET Robot

In a more complex form, another design of the three-wheeled pipe-crawling robot with two arms and two links as illustrated in Fig. 2.10a–b is developed [7]. The shape of this robot resembles the shape of a pair of scissors. This scissor shape helps it to self-adjust the height of the robot when it passes through pipes with varying cross-sectional diameters. In a modified version, levers are used at a fixed angle from the arm to connect arms with the spring (as shown in Fig. 2.10b). It is observed that the lever-based system works more effectively for the generation of traction force.

2.4.3 Differential Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines

Figure 2.11 shows the concept of a differential drive pipe-crawling robot. In this model, three similar kinds of wheel assemblies, circumferentially 120° apart from each other, are used in the robot. The height of the wheel set can be varied by adjusting individual springs for each wheel. The springs are used to maintain traction force on the wheels and also to self-adjust the wheels to pass through the varying diameters of the pipelines.

2.4.4 Robot with Active Steering Capability for Urban Gas Pipelines

Figure 2.12 shows the outline of the steering system of a modular robot called MRINSPECT [8] which is used to carry out inspections inside pipes of diameter 150–200 mm. The entire robot is divided into three modules—driving module, control module, and inspection module. All these modules are connected by

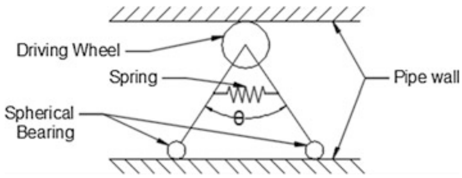


Fig. 2.9 A three-wheeled FERRET–1 robot

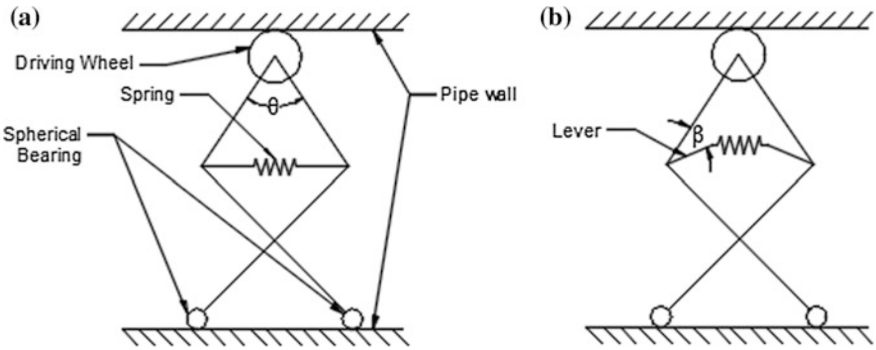
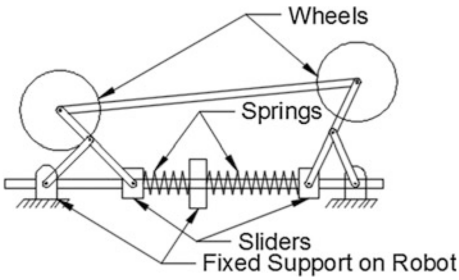


Fig. 2.10 Multi-link scissor-like robot with height control mechanism

Fig. 2.11 Adaptive differential drive system



universal joints. Two sets of driving modules are installed in the front and the rear end of the robot, so that both forward motion and backward motion can be achieved. Each driving module is further comprised of two parts where each part is connected by a double active universal joint. It is specifically used to steer the front part of the driving module through bends and fittings. Active driving force is provided by DC motors, worm gears, and timing belts on the rear part of the driving module. Figure 2.12 explains the pantograph-type leg mechanism for the driving modules. In each part of the driving module, three sets of these mechanisms are installed. A spring is used to provide enough traction force to the robot to crawl through the pipe. Also, it helps to adjust the leg height when the robot passes through the varying diameters of a pipeline. A charge-coupled device (CCD)-based camera is installed on each driving module to record the movement of robot inside the pipe and also to guide the controller in terms of steering the vehicle. Inspection modules are considered optional and can be replaced by an appropriate sensor module as and when required.

2.4.5 A Novel Turbine-Propelled Self-drive Pipe-Crawling Robot

Figure 2.13 describes the design of a passive pipe-crawling robot, which uses the flow of fluids to traverse inside a pipe [9]. One of the key features of the robot is its inclined bristles. These bristles help the robot to traverse in only one direction. Further, a nut, a double screw thread, and a turbine are used to transform the rotational motion of the turbine to translatory motion of the robot. The speed of the robot depends on the pitch of the thread which can be adjusted.

2.4.6 Robot with Active Pipe Diameter Adaptability and Automatic Tractive Force Adjustment

Figure 2.14 shows a novel technique to maintain the tractive force between the pipe wall and the wheels, using parallelogram wheeled leg mechanism, adjusting motor, ball screw, nut, and pressure sensor [10]. Three such assemblies are used which are 120° apart circumferentially. This robot is designed to adjust itself automatically between pipe diameters ranging from 400 to 650 mm; whenever the robot experiences differential diameter, the tractive force between the pipe wall and the wheels changes, which is measured by the pressure sensor located in between the sliding bush and the nut. This change in pressure triggers the adjusting motor to rotate clockwise or anticlockwise according to the requirement, which in turn helps it to maintain the tractive force between the pipe wall and the wheel. The same technique is used to deal with the bends in the pipelines.

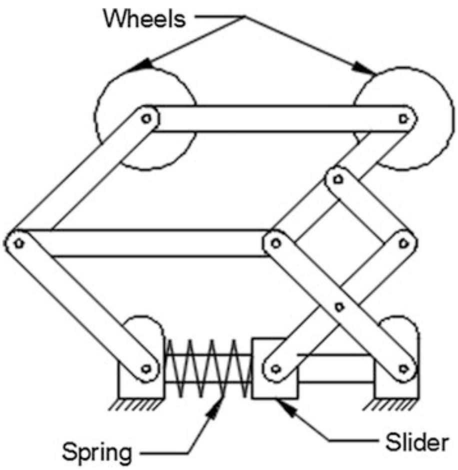


Fig. 2.12 A robot with active steering

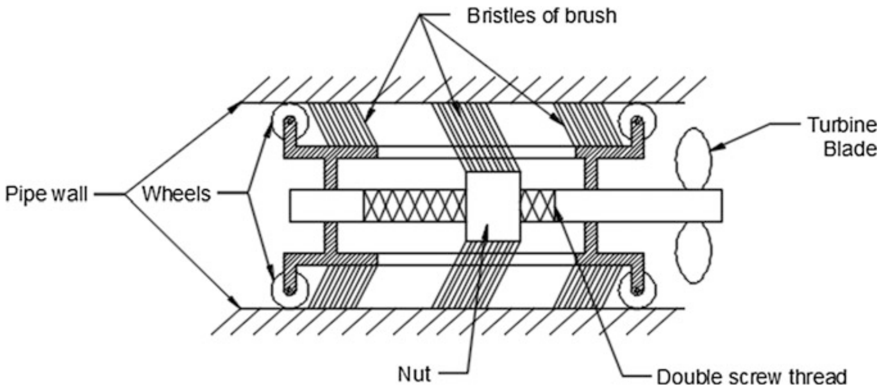


Fig. 2.13 An energy-harvesting passive pipe-crawling robot [9]

2.4.7 Adaptive Mobile Robot for In-Pipe Inspection Task

Figure 2.15 shows the schematic of another novel pipe-crawling robot which is both adaptive in size and capable of clearing obstructions inside a pipe. The robot consists of six sets of such mechanisms 60° apart. Each mechanism consists of three sets of wheels. The first two sets of wheels are termed as rotor outputs 1 and 2, respectively. All wheels in rotor output 1 are inclined with respect to the *z*-axis and fixed to the rotor shaft. This is provided with an intention to achieve spiral movement for the robot as the rotor shaft is rotated which is useful for continuous monitoring. Rotor output 2 wheels are free to rotate about the *z*-axis and get engaged to rotor shaft only when rotor output 1 wheels get stuck. This is achieved by using a set of sun and planet gear combination. Whenever wheels linked to rotor output 1 get locked, rotor output 2 provides extra power to the robot to overcome obstacles. The rear sets of wheels are attached to stator part of the robot on which the actuator is mounted. This novel system also reduces the number of actuators (from 3 actuators to 1 actuator) required to drive a robot inside a pipe. Hence, the power consumption of the robot reduces significantly.

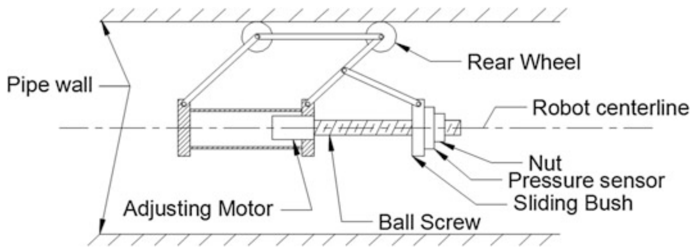


Fig. 2.14 A PCR with adaptive shape and tractive force generation system [11]

2.4.8 *Adaptive Track-Based Robot for In-Pipe Inspection*

The advantage of track-based locomotion is already discussed in Sect. 2.2. A modified track-based pipe-crawling robot is shown in Fig. 2.16. The robot consists of three modules: track driving module, center module, and pantograph connecting module. The track module consists of a frontal track and two rear tracks. Frontal and rear tracks are connected by a compliant active joint. The track module is attached to the center module by pantograph connector. The pantograph connector module also helps the robot to adapt for variable pipe diameters. Three sets of combined pantograph connecting module and track module are attached to the center module at 120° apart. One servomotor is used on rear track of each set of track to provide driving torque to the robot. Transfer of drive torque from rear to front track is achieved by a set of gears. By rotating the lead screw in clockwise or anticlockwise direction, the legs of pantograph can be brought closer or apart, which in turns helps the robot to adapt inside varying cross section of pipes.

2.4.9 *Micro-In-Pipe Robot Based on Shape Memory Alloy Actuator*

Figure 2.17 shows a shape memory alloy (SMA) spring-based mini-pipe-crawling robot which can crawl inside pipes of diameter varying from 50 to 80 mm [13]. The robot is divided into two identical parts called gripping module and driving module. The gripping and driving modules are connected using four SMA springs. During the motion of robot, only one module is engaged to the pipe and other move by compressing or expanding the SMA springs. Each gripper consists of friction spring strips, an electromotor, and a strap. The electromotor is used to wind or unwind the strap which in turn changes the distance between lower and upper cover of the gripper. This results in change in curvature of friction spring strips which causes the gripper to grip or release. Four two-way memory effect SMA springs are used to connect the two grippers. These springs can compress or expand to bring the grippers closer or apart. Compression and expansion of springs are controlled by varying the temperature of the springs, which is achieved by passing current

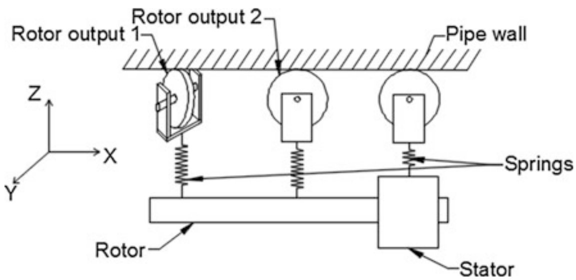


Fig. 2.15 Adaptive, obstacle clearance system

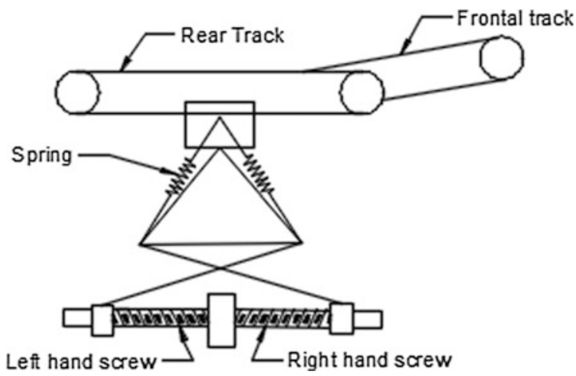


Fig. 2.16 A track-based adaptive pipe-crawling robot [12]

through the spring wires. For steering, the robot springs are selectively compressed. These types of robot are energy efficient and compact. Hence, such robots are effective for pipes of lower diameter. A speed close to 3 mm/s is reported to be achieved in this system.

2.4.10 Multi-functional Pipe Investigation Robot (PIR) with Linkage-Type Mechanical Clutch

Figure 2.18 shows a linkage-type mechanical clutch system [14], which helps the vehicle to operate in two different modes: locomotion mode and retrieval mode. Drive wheels are used for forward and backward locomotion of the vehicle. The rear and clutch wheels are idle wheels. There are two sets of mechanisms highlighted in Fig. 2.18. The mechanism with red border is basically a five-bar linkage mechanism, which is used to adjust the height of the vehicle and keep the line joining centers of rear idle wheel and drive wheel parallel to the axis of the vehicle. The mechanism highlighted in blue border is a four bar mechanism and is used to adjust the height of the clutch wheel. Once, height of the set of drive wheel mechanism is lowered, due to the presence of four bar mechanism in clutch wheel, its height raises. Hence, when the drive wheel set disengages from pipe wall, the clutch wheel system gets engaged, making it easier to drive the vehicle out of pipe by simply pulling it from the back.

2.4.11 Planar Multi-functional PIR with Two Sets of Wheels

Figure 2.19 shows a drive mechanism based on only two sets of wheel assembly (180° apart). Using two sets instead of three provides more space to mount sensors

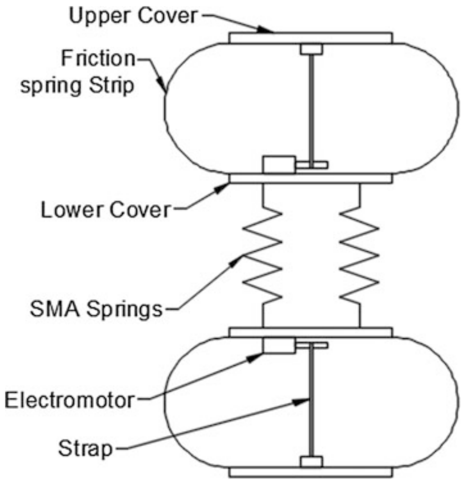


Fig. 2.17 A shape memory alloy-based micro-adaptive pipe-crawler

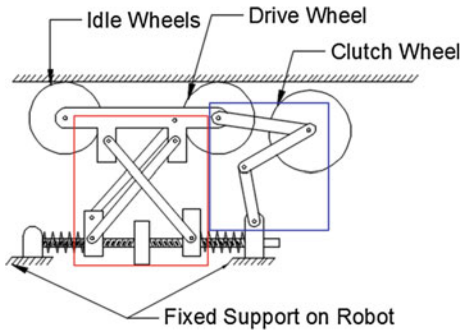


Fig. 2.18 A multi-functional PIR

and also reduces design complexities. Each set of wheel assembly consists of a pair of wheels where the front wheels are used to steer the robot and rear wheels are used for driving the robot. This small robot is developed to travel inside a medium-sized pipe of internal diameter 100 mm. Depending on the direction of steering wheel, the robot can travel in a helical or straight path. Steering wheels are also used to turn the robot in elbow or T-joints. Working of this robot is categorized into three parts, i.e., driving, detecting, and searching mode. The robot is equipped with three cameras, one at the front and two at the sides. In the detecting mode, the front camera locates the defect, while to collect detailed information of defect the two sidewise cameras are used.

2.4.12 Planar Adaptive Mechanism for an In-Pipe Robot

Another novel planer mechanism, consisting four wheels, is described in Fig. 2.20. Four external arms are hinged to the vehicle body and the wheels are attached to the arms by a U-frame arrangement. It is also referred as adaptable quad arm mechanism. Here, all four wheels are actively driven by separate motors. By controlling the direction of rotation of wheels, the robot can be made to move forward/ backward or the horizontal distance of the wheels can be varied. This mechanism allows the robot to travel through bends of zero radius of curvature and bends of varying diameter. Since each wheel can steer with respect to arms, the mechanism is termed as swivel hand mechanism. This mechanism allows the robot to drive in a spiral motion and also helps to orient inside the pipe.

2.4.13 Peristaltic Pipe-Crawling Robot for Long Distance Inspection of Sewer Pipes

A novel peristaltic pipe-crawling robot is designed and fabricated for the inspection of small pipelines (<70 mm diameter) [15]. Locomotion of this robot is inspired from the movements of earthworm. The important member responsible for such movement is the artificial muscle, which is made up of micro-carbon fiber and low ammonia natural rubber latex. Figure 2.21a explains the arrangement of fibers and latex of artificial muscle. Driving units are actuated by compressed air. Components of a unit of this robot are described in Fig. 2.21b. The entire robot consists of six such units, and a camera is mounted on the front unit for inspection of pipeline. Electrically controlled valves are used to inflate or deflate artificial muscle. Since carbon fibers do not elongate, the rear and front part of a module comes closer when a module is inflated and vise versa. This helps the modules to grip the pipe wall and move the robot forward.

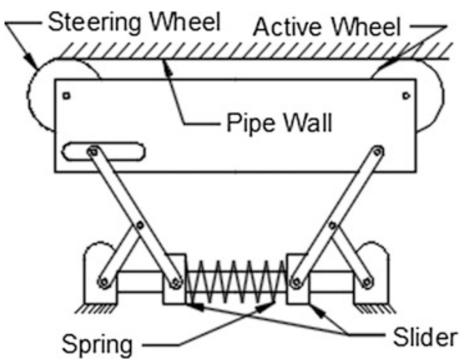


Fig. 2.19 A planar PHMR

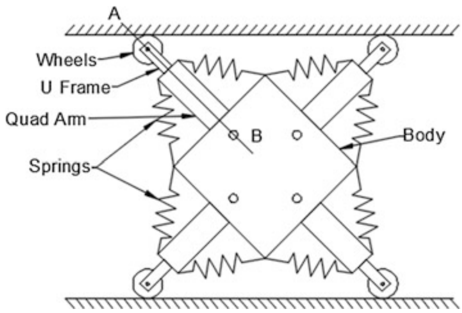


Fig. 2.20 Another planar mechanism with adaptive locomotion capability

2.4.14 Inchworm-Based Vertical Climbing Robot with Adaptive Size

Figure 2.22 shows the design of a robot whose crawling mechanism is based on an inchworm. The robot consists of two clamping devices, two universal joints, and an expansion device. Compressed air is used as a source of energy for driving the robot. The clamping device is based on a four bar mechanism. Figure 2.22 shows the assembly of clamping device. Three sets of this mechanism are mounted on each set of clamping device. The clamping devices produce enough traction force for the robot to enable it to climb along a vertical pipe carrying its weight along with tether cables and sensors. This robot has been shown to traverse inside a pipe of diameter varying from 100 to 300 mm.

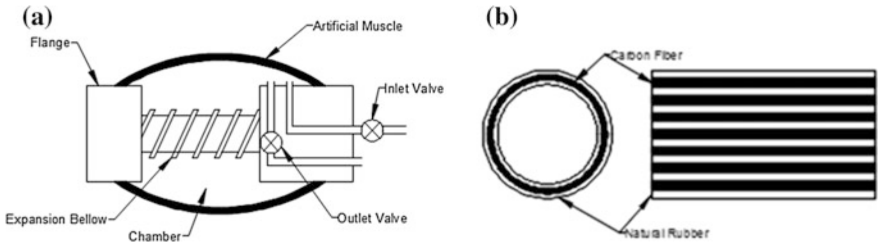


Fig. 2.21 A peristaltic PHMR: **a** transverse cross-sectional view and **b** longitudinal cross-sectional view

2.5 Various Types of Wheel Assembly for the Pipe-Crawling Robots

Wheels can be viewed as the dynamic interfaces between the health monitoring system and the inner surface of the pipeline. Similar to the ground vehicles, a good design of wheel assembly ensures less vibration and noisy operation of the robot. In this section, we will take a closer look on the wheel assembly of various types available for the crawler robots. The entire section is divided into three subsections: First, we will briefly discuss the major challenges faced during the inspection process; next, we will deal with various types of wheel assemblies; and finally, we will present a comparison table which shows the cumulative advantages and disadvantages of a few wheel assembly systems.

2.5.1 General Challenges Faced by the Pipe-Crawlers

The following are the major challenges faced by the pipe-crawlers inside the pipelines:

- Wear and tear due to long distance travel inside the pipelines,
- Continuous position monitoring of the robot for location indication,
- Slippery inner walls of the pipeline causing unstable motion,
- Turns and bends in the pipeline,
- Non-uniform gas flow,
- Turbulence of the gas flow, and
- The presence of corrosive agents.

In what follows are brief descriptions of various wheel assembly systems designed for this purpose.

2.5.1.1 Single-Body Three-Wheeled System

A simple three-wheeled model generally consists of wheels connected with springs attached to the main body, to accommodate any small changes in the pipe diameter (Fig. 2.23). However, this simple arrangement is often not enough to adapt with the large changes in the pipe diameter. Therefore, the basic model has to be corrected and modified to face these challenges. There has to be a mechanism, which can move the whole frame of the robot so as to change the radius of the robot.

The movement of the robot can be carried out with the help of an adaptive mechanism by actuating the pipe diameter adjustment of the tractive force. A stepper motor is used for pushing the spring, which in turn causes the increase in

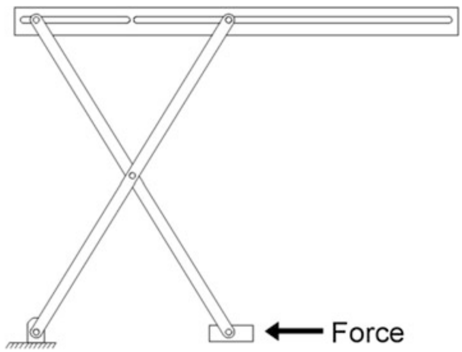


Fig. 2.22 Inchworm-based crawling mechanism

the tractive force exerted on the walls of the pipe. The inspection robot has to change its diameter in order to mitigate various obstacles such as changing pipe diameter, bends, curves.

2.5.1.2 Multi-sectional Wheeled Robot

This type of wheel system ensures active steering capability and diameter adaptability. The robot is designed as a serpentine structure (Fig. 2.24) [16]. Two active driving vehicles are located in the front and rear of the system, respectively, which provides sufficient traction for the entire robot. In this robot, the steering mechanism is based on double active universal joint, which provides omnidirectional steering capability. This system helps to mitigate challenges/defects such as branching,

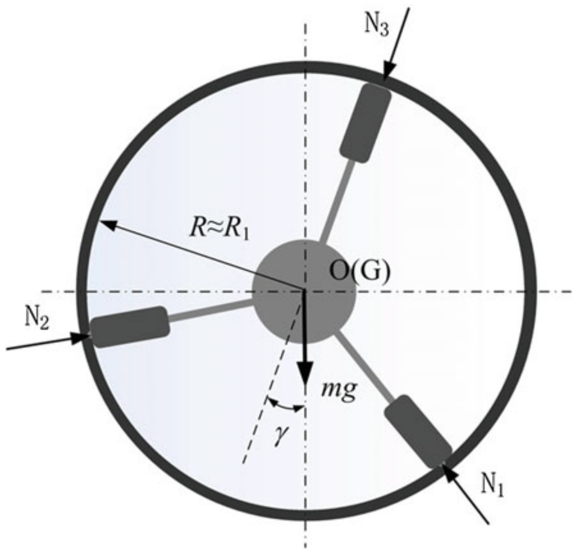


Fig. 2.23 Front view of a single-body three-wheeled crawler system

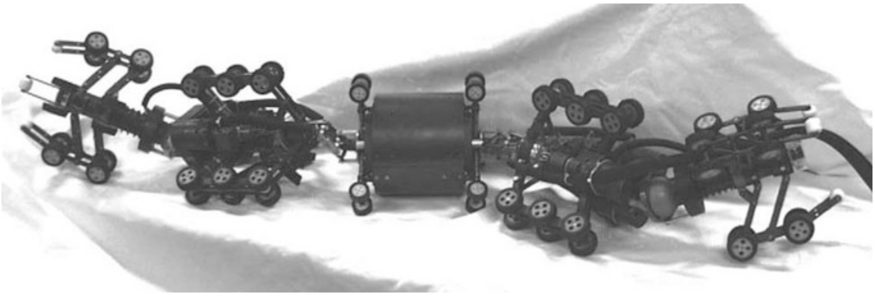


Fig. 2.24 View of a multi-sectional wheeled robot

passing through the reducers, and valves with mechanical damages such as dents, gouges.

Various segments of the driving module are connected with universal joints. Both the front and rear segments have three-wheeled leg mechanisms. The three-wheeled mechanism continuously expands and contracts according to the terrain of the inner walls of the pipes. In this robot, the traction force is mainly created by the wheels on the legs which are actuated by a DC motor in the rear segment. The power of the motor is evenly transmitted via worm gear mechanism.

2.5.1.3 Robot with Annular Wheeled System

This system mainly consists of two parts—the stator and the rotor, connected by an active joint including a DC motor with a reducer and, in some cases, a universal joint [16]. The stator has a set of wheels which provides motion along the axis of the pipe, whereas the rotor is equipped with wheels tilted at a small angle with respect to the plane perpendicular to the axis of motion. This setup ensures the constraining of the stator so that while it moves along the tube axis, the wheels of the rotor move along a helical path (Fig. 2.25).

The wheels on the stator and the rotor are present to guarantee stability against overturning. Universal joints are provided for locomotion if there are small diameter pipes with abrupt changes in the angles of the pipes.

2.5.1.4 Wheelless Pipeline Inspection and Condition Analysis System

This system is generally used for small diameter water pipe inspection (Fig. 2.26) [17]. It uses remote field technology (RFT), in which no contact is required with the walls. It is insensitive to the presence of boundary walls and therefore suitable for thinning detection. It is waterproof and can measure through wax or sand and

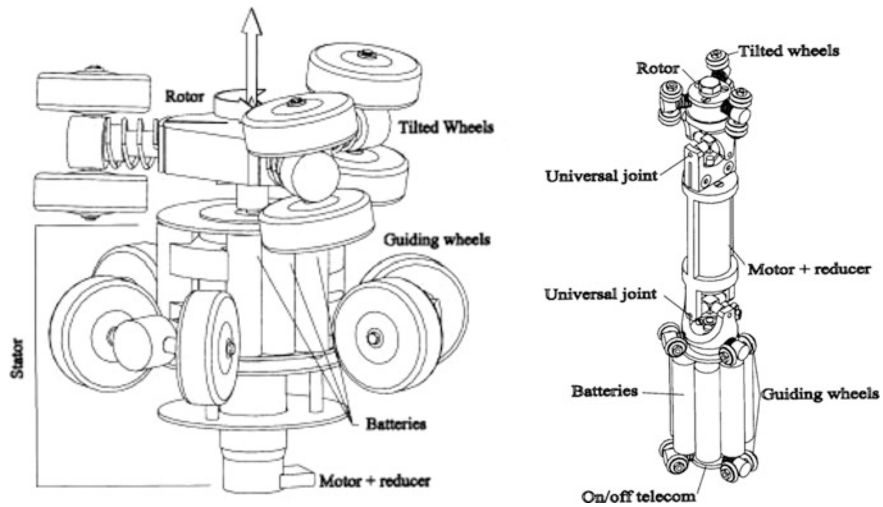


Fig. 2.25 Robot with annular wheeled system

Fig. 2.26 A wheelless pipeline inspection system

magnetic liners. This robot is suited for both cast and ductile iron pipelines. It needs a very small pushing by product flow/air pressure (about 2 bar). It is reported to have a speed of around 1–2 km/h.

2.5.2 Performance Summary

A brief performance summary of the four systems discussed above is provided in Table 2.1.

Table 2.1 Performance comparison of various drive systems

Model-1 (ref. 5.2.2.1)	
Advantages • Low weight • Simple construction	Disadvantages • Poor diameter adaptability • External power is required
Model-2 (ref. 5.2.2.2)	
Advantages • Easy steering • Diameter adaptability • Modular system	Disadvantages • Heavier system • Low speed due to poor friction • External power required
Model-3 (ref. 5.2.2.3)	
Advantages • Compact and lightweight • Diameter adaptability • Good friction characteristics	Disadvantages • External power required • Complex system
Model-4 (ref. 5.2.2.4)	
Advantages • Lightweight • No requirement of external power • Diameter adaptability • Easy steering	Disadvantages • Needs enough pushing force • Less sensitive for large diameter pipes • No speed control. Braking system

2.6 Various Sensing Mechanisms Used in Pipe-Crawlers

A functional and autonomous robot for SHM needs to carry with it an array of sensors, data recorder, communication system, power supply, etc. However, a single robotic unit cannot carry all the instruments as the load-carrying capacity of any robot is quite limited either due to the limitation of propulsive force or due to the limited power supply. This is the reason why such robotic systems are generally modular in nature. A typical robot consists of four types of modules, i.e., tractive vehicle, ultrasonic testing vehicle, control vehicle, and coupler module. In last few sections, we had focused on various technologies applied for the locomotion of the robot. In this section, we will discuss the sensing systems applied for the SHM of pipe surface.

Typically, for sensing of defects in gas pipes, the following systems are used:

(a) Optical Sensing

- Visual inspection-based sensing,
- Laser profiling,
- Microwave sensing.

(b) Vibration and Sound Wave-based Sensing

- Sonar profiling,
- Ultrasonic sensing,
- PVDF-based vibration sensing.

(c) Indirect Sensing

- Magnetic flux leakage sensing,
- Villary sensing,
- Gas sensing.

In the following section, we will provide brief description of some of these sensors.

2.6.1 Visual Inspection of Pipe Health Conditions

The biggest challenge of optical scanning in pipelines is the absence of proper illumination. As shown in Fig. 2.27, servo-controlled cameras with night mode are generally used for visual inspection of pipe surfaces. These cameras provide the ability to have a real-time view of the piping system and are able to record both images and videos. Camera tractors are used frequently in sewer pipe health monitoring. The crawler moves inside the pipeline by using two sets of belt-driven systems. An external power cable is attached to provide power for motion and camera. A major challenge in this type of sensing system is the selection of proper camera lenses. Most of the lenses being fish-eye-type provide unnecessary details of the open part of the pipe and less details of the pipe surface. Several omnidirectional cameras with cylindrical strip vision have been recently designed to overcome this problem.

2.6.2 Laser Profiling Sensor

This type of sensing is used for indicating deformations and corrosion inside the pipeline with high precision and for a broad range of diameters. The laser profiling is reported to measure the diameter and concentricity of the pipe ranging from 100 mm to 4 m diameter, performing up to 250,000 measurements per min with

Fig. 2.27 Visual inspection system

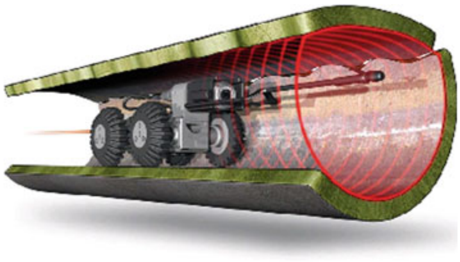


Fig. 2.28 A typical laser profiler

±1% accuracy! The output data are generally collected over the entire length of the pipe and can be used to generate statistical reports, as well as 3D visualization of the interior wall of the pipe. For an effective 3D visualization, however, multiple lasers are used that can measure deformations based on optical triangulation. In some literature, the use of rotating multiple lasers is proposed which along with forward-moving probes can generate high-precision mapping of the pipe surface (Fig. 2.28).

2.6.3 Sonar Pipe Profiling

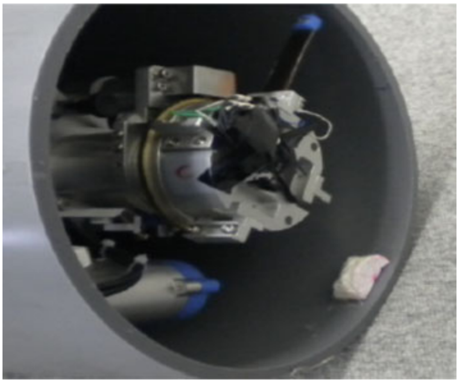
Sonar sensors are mainly used for underwater pipe profiling where CCTV cameras are not useful, particularly in pipes carrying murky fluids. Often, it is also used along with laser profilers. This system utilizes high-resolution and short-range sonar for real-time cross-sectional views of the pipe. This type of sensor can be used in submerged and semi-submerged pipelines ranging from 200 mm and above. The system consists of piezoelectric transducers which generate a characteristic acoustic signal and measure the reflection of the same from the pipe surface. It provides accurate dimensional data on grease accumulation, blockages, pipe deformation, etc., thereby providing a 2D profile of the interior of the pipe wall (Fig. 2.29).

2.6.4 Polyvinylidene Difluoride (PVDF) Sensor

PVDF is a relatively low-cost polymeric piezo-sensor which generates output voltage in the range of few volts when the sensor probes scan the pipe inner surface

Fig. 2.29 A typical sonar profiler

Fig. 2.30 A PVDF sensor-based robot



(see Fig. 2.30) [18]. These types of sensors are usually supplied in the form of thin film, typically ranging from 9 to 110 μm thicknesses. Specially designed cantilever beam surface coated with PVDF films is used as rotating sensory probes. The electrical charge generated in the PVDF strip is proportional to the change in the mechanical stress. Hence, this sensor can be used to detect finite projections in the pipe surface. One of the attractive features of this sensor is that it is much less data-intensive and hence can be used for very long-range scanning applications.

2.6.5 LIDAR (Light Detection and Ranging)

LIDAR is a remote monitoring technology that basically measures the distance of a target by illuminating it with a laser and analyzing the reflected light. LIDAR sensing uses ultraviolet, visible, or near-infrared light to image targets and can be used with a wide range of objects, including nonmetallic objects, chemical compounds, clouds, rocks, rain, and even single molecules. Airborne LIDAR Pipeline Inspection Service is based on a mid-infrared Differential Absorption LIDAR (DIAL) chemical sensor. The principle of DIAL is based upon the selective absorption of laser light by different chemicals. During operation, the laser beam is transmitted down from the aircraft to illuminate the area on the ground above and around the buried pipeline. The light reflected from the ground is collected by the receiver of the sensor, and the amount of reflected energy is thus measured. If the laser beam passes through a gas plume leaking from a pipeline, the received energy will be diminished due to the absorption of the laser light in the plume. This absorption signature is used to locate the leak and assess its magnitude (Fig. 2.31).

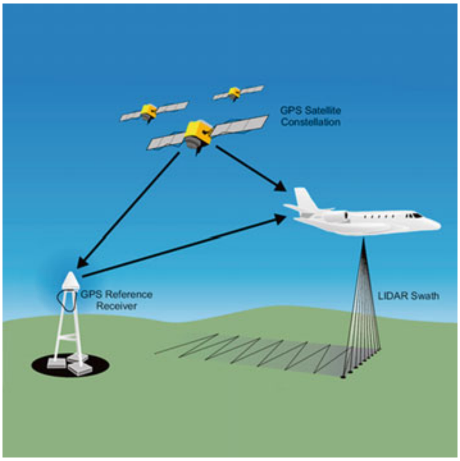


Fig. 2.31 LIDAR sensing of pipe faults

2.6.6 Ultrasonic Sensors

Ultrasonic rotating scanners are used to generate detailed three-dimensional scan of the internal pipe surface in order to detect minute deformations and cracks inside the pipe wall. Often, a laser-based excitation system is used to generate ultrasonic stress waves that can travel through the pipe (Fig. 2.32). The waveform is generally referred as guided ultrasonic wave (GUW) as the pipe boundary essentially works like a waveguide during wave transmission. Due to constructive and destructive interference, the sound intensity varies non-uniformly in the 'near-field' region. However, beyond a critical distance, the intensity becomes quite uniform, which is known as far-field region. Any flaw located in the 'far'-field region is more detectable. Piezoelectric sensors are generally used to study the nature of the wave front. In the presence of anomalies, like cracks, the waveforms get distorted which can be captured by the piezoelectric sensor. The advantage of this system is that it does not need any reference data for the prediction of anomalies. The inspection

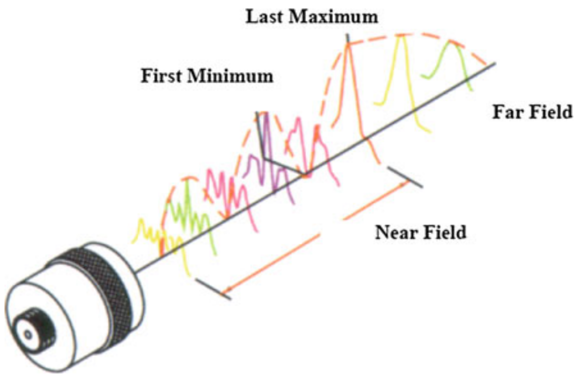


Fig. 2.32 Ultrasonic transduction system

process consists of creating a series of consecutive axial views to create a 3D image of the internal pipe wall which is later analyzed by an expert or by an automatic diagnostic system.

2.6.7 Acoustic Leak Detection

A leak inside a pressurized pipeline produces an acoustic signal (Fig. 2.33). This acoustic signal is created by the pressure difference inside the pipeline and the atmosphere outside the pipe. While the crawler traverses the pipeline, it continuously records this acoustic data which is analyzed to identify changes in acoustic signals. Whenever a crawler approaches, leakage intensity of the detected acoustic signal increases. The acoustic signal reaches its peak at the point at which the crawler passes the origin of the leak and then diminishes as the crawler moves away from the leak. In the following section, we will briefly compare the merits and demerits of various sensing systems.

2.7 Merits and Demerits of Various Sensing Techniques

Various sensors that we have discussed so far even though are broadly applicable for all pipe inspection robots; each sensor has its own advantages which should be considered based on application scenario and constraints. Table 2.2 provides a brief overview on relative merits and demerits.

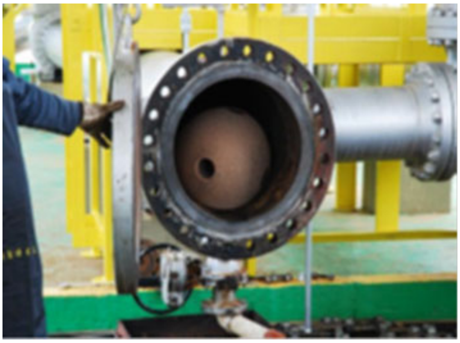


Fig. 2.33 Acoustic leak detection system

Table 2.2 Brief performance summary of the sensors

S. No.	Sensor	Merits	Demerits
1.	Visual inspection	• Real-time monitoring • Unaffected by pipe traffic disturbance • High reliability	• Variable camera settings according to pipe size • Color of videos vary with power consumption • Requires high data storage capacity (normally 300 m/GB) • Due to high-power requirements, a power cord and video cable are always attached with the crawler
2.	Laser sensor	• Wider range of anomalies • High accuracy • High sensitivity (1 million measurements in every 4 min) • High speed of measurement	• Works only above flow lines • Power cable attached with crawler • High-power consumption • Requires additional machine vision software to generate digital pipe profile
3.	Sonar profiling	• High range • Average accuracy • Works under flow lines	• Requires supporting sensor data for accurate profiling • Power cord is attached with crawler • Signal loss occurs due to cancelation of waves reflected from different parts
4.	PVDF	• Low-power requirement • High sensitivity • Can work in rough environments • Low data output and hence less memory space requirement	• Medium–low inspection speed • More efficient in detecting positive growths • Frequent calibration is needed
5.	LIDAR	• Works best when there is existing leakage in pipeline • Highly sensitive	• Cannot be used in autonomous pipe health monitoring • High cost of operation
6.	Ultrasound sensor	• High sensitivity • Accurate modeling • Advance detection of cracks	• Large inspection time • High-power consumption • Inaccurate in the presence of certain types of anomalies like pipe joints
7.	Acoustic leak detection	• Accurate in advance leak detection • No external power is required	• Additional accessories required for position tracking • Efficient only when there is already a gas leakage

2.8 DVSS (Digital Visual Sidewall Scanning)

In the earlier sections, we have discussed the crawler robot and the sensors for carrying out automated pipe inspection. However, post-processing of the obtained data is often an equally challenging task. The experts are expected to go through extensive video data recorded for hundreds of kilometer of pipelines and detect anomalies of submillimeter size! An efficient post-processing requires an integration of efficient video-sensing (such as use of fish-eye camera, diffuse wide angle illumination) with intelligent recording, digital conversion of the data with facility for high-resolution inspection of selected critical locations. Digital visual sidewall scanning (DVSS) [19] provides an extremely reliable and convenient method for gathering visual data from within a pipe by implementing a digital image processing to deliver rich information in a format that is easy to analyze. When an area of the thumbnail is clicked, a detailed view of that region appears in the analysis pane, and a corresponding down pipe view appears alongside it. In this pane, the analyst can scroll the view in either direction and zoom in on specific regions for better inspection of the damages (Fig. 2.34).

2.9 Microwave Sensor

Microwave sensors are generally used for the inspection of thinning of the pipe wall (PWT). It detects 'invisible' damages up to 10 cm behind the pipe wall. With the help of transmitting antennas, continuous 2.45 GHz CW radar signals are sent through the pipelines. The backscattering signals obtained by the four displaced signal receiving antennas provide information regarding anomalies inside and outside of the pipe (Fig. 2.35).

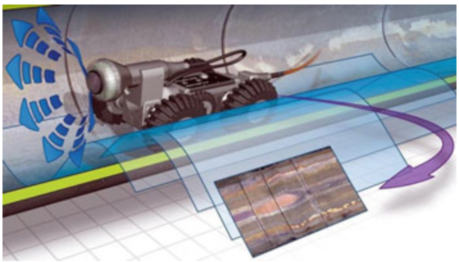


Fig. 2.34 Digital visual sidewall scanning [19]

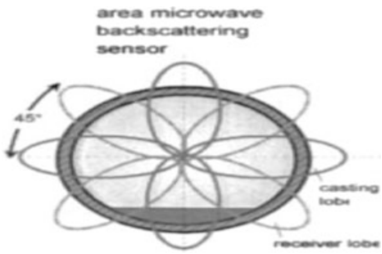


Fig. 2.35 Microwave sensing

2.10 Summary

In this chapter, we have provided an overview of pipe health monitoring systems mainly for oil and gas pipelines. We have first described the significance of such monitoring systems in view of the exponential growth of fuel pipelines and increased concern about the safety and performance of such systems. Subsequently, we have outlined the basic mechanisms corresponding to various pipe-crawling robots and focused on a few widely used models. Some of these models are later developed as multi-functional system; such that in addition to forward motion, the robots are designed to have capabilities such as adaptive size control, steering mechanism for pipe bents, and obstacle clearance system. Next, we have discussed various wheel configurations utilized with these robots and a performance comparison of such systems. Finally, we have described the sensors commonly deployed with these robots and a broad comparison of their characteristics. A few associated issues like digital signal processing systems and more advanced detecting systems based on microwave are briefly touched at the end.

Model Questions

1. What is the significance of pipeline health monitoring for oil and natural gas supply? Briefly describe the national and international scenario.
2. Write various processes/techniques that can be used for fault detection in pipelines. What is structural health monitoring? How SHM can be used for pipeline health monitoring?
3. What is in-line pipe health monitoring? What are the advantages of in-line health monitoring? Write about three types of in-line health monitoring.
4. What are traditional locomotion systems? Compare the performances between propulsion-driven PIG and belt-based PIG.
5. What are non-conventional locomotion systems? Where are they applicable? What is a Smart-ball Technology for PIG? Are Smart-balls suitable for natural gas pipelines?
6. What is an active steering system? Where are they applicable? Compare between the performances of MOGRER and FERRET robots.
7. What are multi-functional Pipe Investigating Robots? Give two examples of such PIRs and discuss their applicability.

8. What are the general challenges faced by designers for PIR locomotion? Describe two wheel assembly systems commonly used.
9. What are the various sensing mechanisms used in the pipe-crawling robots? Describe any three such sensors and indicate their advantages and disadvantages.
10. What is DVSS? How this is used for pipeline inspection?

References

1. (2012) Gas and liquid transmission pipelines. Thompson
2. http://www.nrec.ri.cmu.edu/projects/explorer/description/
3. www.robaid.com/bionics/tbcp-ii-robot-uses-gecko-tape-coated-belts-to-climb-smooth-surfaces.htm
4. http://spectrum.ieee.org/automaton/robotics/robotics-hardware/speedy-inchworm-robot-only-needs-one-motor
5. http://www.puretechltd.com/products/smartball/smartball_leak_detection.shtml
6. Okada T, Kanade T (1987) A three-wheeled self-adjusting vehicle in a pipe, FERRET-1. Int J Robot Res 6(4):60–75
7. Okada T, Sanemori T (1987) MOGRER—a vehicle study and realization for in-pipe inspection tasks. IEEE J Robot Autom RA-3(6):573–582
8. Fujiwara S, Kanehara R, Okada T, Sanemori T (1993) An articulated multi-vehicle robot for inspection and testing of pipeline interior. In: Proceedings of the 1993 IEEW/RSJ international conference on intelligent robots and systems, pp 509–516
9. Zheng Hu, Appleton Ernest (2005) Dynamic characteristics of a novel self-drive pipeline pig. IEEE Trans Rob 21(5):781–789
10. Zhang Yunwei, Yan Guozheng (2007) In-pipe inspection robot with active pipe-diameter adaptability and automatic tractive force adjusting. Mech Mach Theory 42(12):1618–1631
11. Kim YJ, Yoon KH, Park YW (2009) Development of the inpipe robot for various sizes. In: IEEE/ASME international conference on advanced intelligent mechatronics, pp 1745–1749
12. Roh S, Kim DW, Lee JS, Moon H, Choi HR (2009) In-pipe robot based on selective drive mechanism. Int J Control Autom Syst 7(1):105–112
13. Yu-xia Z, Guang-ping H, De-wen G (2009) Micro in-pipe robot mechanical structure design of shape memory alloy driving. In: Proceedings of the 2009 IEEE international conference on robotics and biomimetics, 19–23 Dec 2009, Guilin, China
14. Choi HR, Roh S (2007) In-pipe robot with active steering capability for moving inside of pipelines. In: Habib MK (ed) Bioinspiration and robotics: walking and climbing robots. ISBN 978–3-902613-15-8, p 544, I-Tech, Vienna, Austria, EU, Sept 2007
15. Matos J, Tosunoglu S (2011) Peristaltic crawler for piper-line unplugging. ASME Early Career Tech J. In: ASME early career technical conference, ASME ECTC 4–5 Nov 2011, Atlanta, Georgia USA
16. Choi HR, Ryew SM (2002) Robotic system with active steering capability for internal inspection of urban gas pipelines. J Mechatron 12(5):713–736
17. Liu Zheng, Kleiner Yehuda (2013) State of the art review of inspection technologies for condition assessment of water pipes. Measurement 46:1–15
18. Agarwal V, Ogai H, Nishijima K, Bhattacharya B (2011) Inspection of pipe inner surface using advanced pipe crawler robot with PVDF sensor based rotating probe. Sens Transducers 4(127):45–56
19. http://www.pipelineandgasjournal.com/digital-visual-sidewall-scanning-streamlining-collection-and-analysis-inspection-data

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